Modeling coupled Thermo-Hydro-Mechanical processes including plastic deformation in geological porous media

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OUTLINE

- Motivation
- Conservation Equations
- Approach to Modeling
- Plasticity-Permeability Model
- Geothermal Example
- Effects of Plasticity
- Future Work
- Conclusions

MOTIVATION

Dominated by Faults/Fractures

Oil and Gas

Geothermal

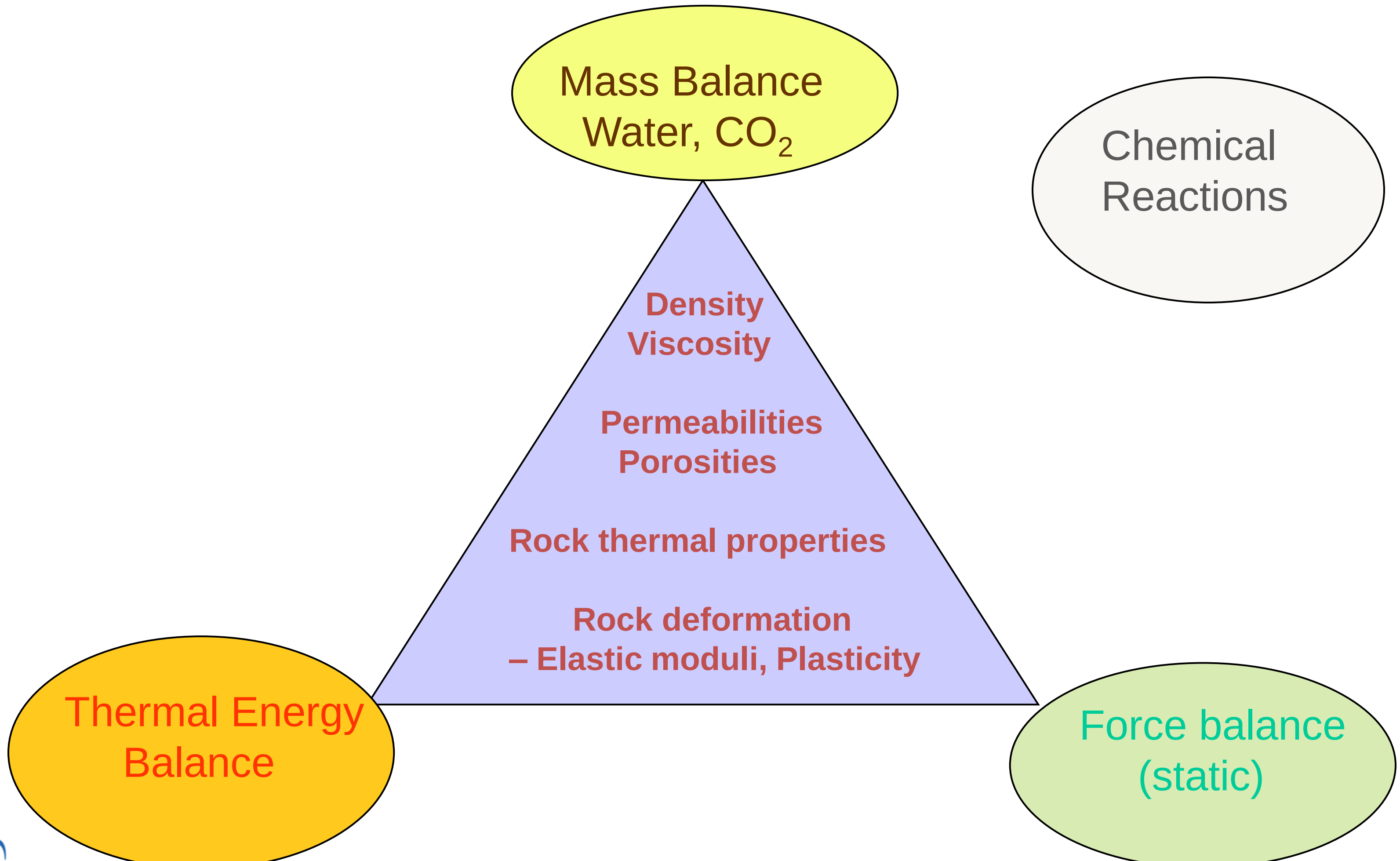
CO2 sequestration

Nuclear waste

Arctic Permafrost

Characteristics strongly dependent on pressure, temperature, composition, stress
e. g. Permeability, Connectivity, Porosity, Surface Area, Stress-Strain relationships

CONSERVATION EQUATIONS
Coupled and Nonlinear



pressure, temperature, composition, stress, deformation

How Coupling Occurs in Equations

Explicit terms in equations
e.g. effective stress and thermal stress in the Force Balance

Dependence of coefficients
e.g. ϕ (ε,σ ,p,T)   K (ε,σ ,p,T)   E (ε,σ ,p,T)
EOS

In fractured media, permeability has power (cubic or higher) dependence on aperture . Growing body of literature, a number of permeability-deformation models

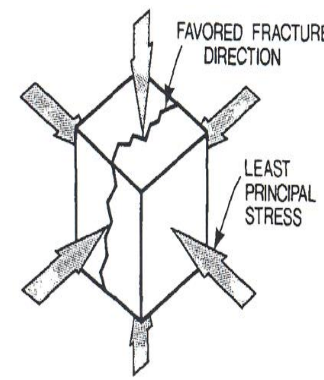


Figure 1. Stress element and preferred plane of fracture (after Hubbert and Willis, 1957).

MODELING CHALLENGES

Large changes in fluid pressure

Large changes in temperature

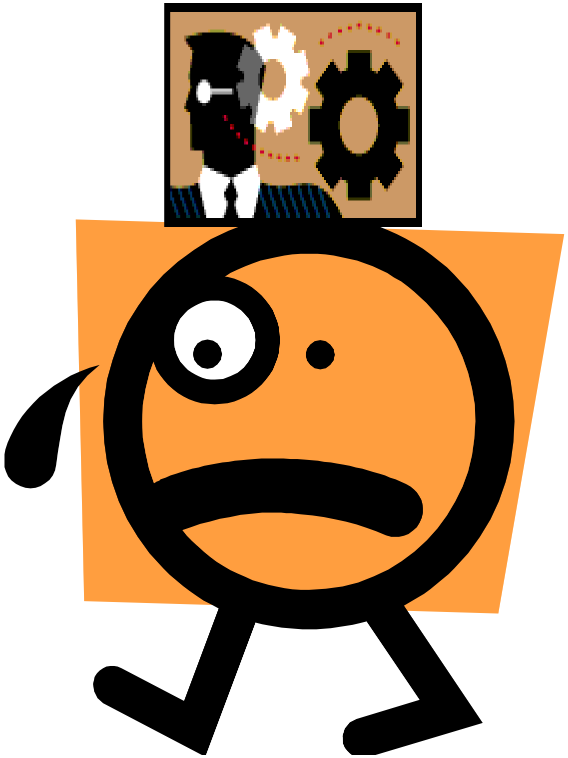
Large changes in stress

Large problem size

Highly nonlinear

Many different space and time scales

Matrix rock and fractures/faults are both important



OUR APPROACH TO MODELING

Continuum– dual porosity/permeability

Full Jacobian – Newton-Raphson: choose levels of coupling

Efficient evaluation of functions

CV – FE, fixed grid

Static force balance – elastic/plastic, small strain

Code used and verified on a variety of projects including Geothermal, CO_2, Nuclear waste, Oil&Gas, ER, Arctic permafrost, Hydrates

A Description of FEHM

Subsurface physics
Mass and Heat - Multi-phase, multi-fluid
Rock deformation-elastic/plastic
NAPL, Hydrates, Coal-Bed Methane

Multiple Scale
Dual Porosity
Dual Permeability
Generalized Dual Porosity
Flux-continuous Anisotropy (CVFE based)

Fluid properties
Rational polynomial fit to water/steam/CO_2 data
Functions of Temperature and Pressure

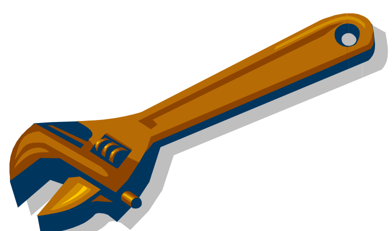
Solution of Equations

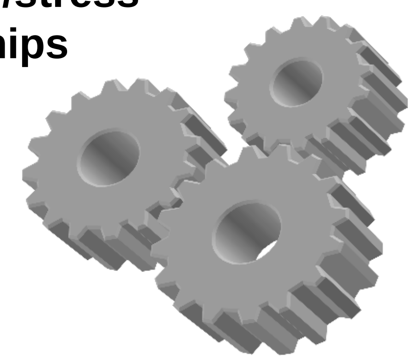
- –Pre-conditioner accelerated for the linear equations.
- –DOF reduction techniques
- –Newton-Raphson for the nonlinear equations.

Advective Transport

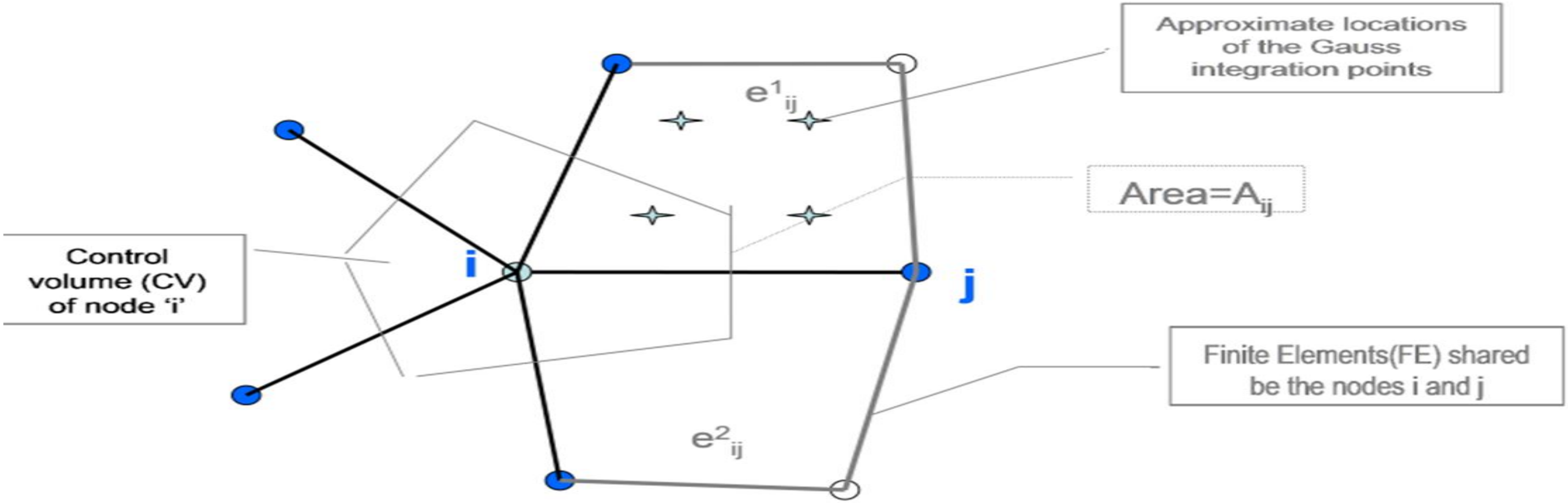
- –Multiple reacting species
- – Particle Tracking on non-orthogonal grids, including dispersion and diffusion

Choice of permeability/stress-deformation relationships





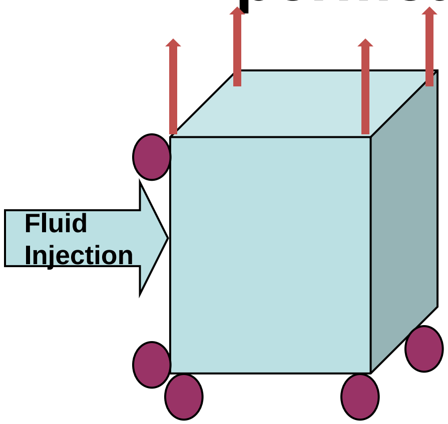
Coupling Fluid Flow and Deformation



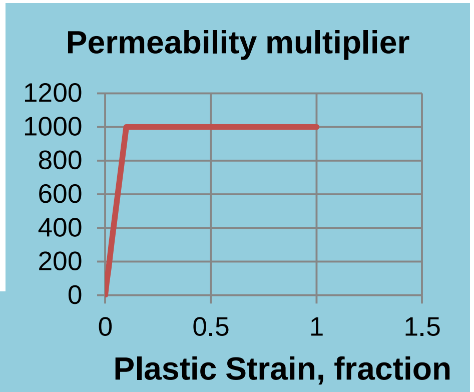
NOTE: In FEHM, properties are input at nodes and assigned to the CV. properties on FE are obtained by using appropriate averages/interpolations

Drucker-Prager Plasticity model

permeability = f (accumulated plastic strain)



unit cube, E=10000 Mpa, Nue=0
K_{init} =10^{-14} m^2, Injection rate = 0.4 kg/sec



Consistency Check

$$\sqrt{J_2} \le -\eta * \frac{1}{3}\sigma_{kk} + \xi * C$$

$$\eta = 0.1,\ \xi = 1.0,\ C = 10.0$$

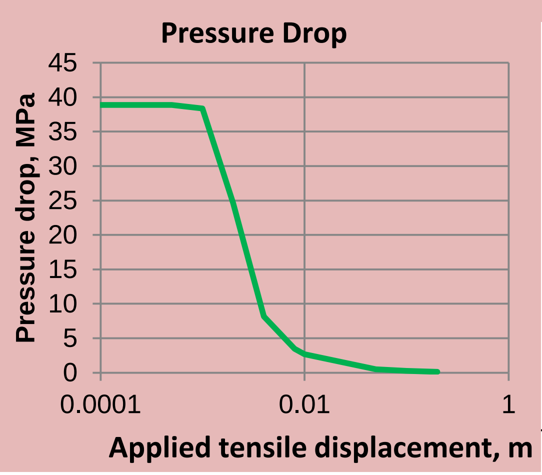
$$\sigma_{xx} = \sigma_{yy} = 0,\ \sigma_{zz} = 16.375(tension)$$

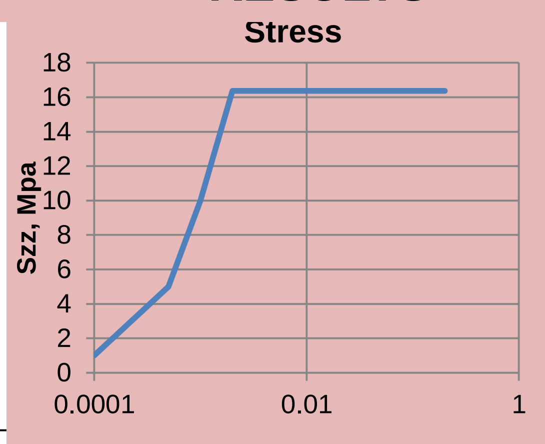
$$\frac{1}{3}\sigma_{kk} \approx 5.46MPa$$

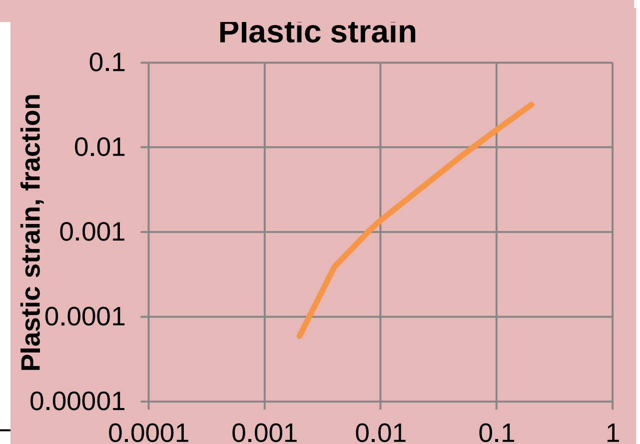
$$\therefore -\eta * \frac{1}{3}\sigma_{kk} + \xi * C \approx 9.45MPa$$

$$\sqrt{J_2} \approx 9.47$$

RESULTS

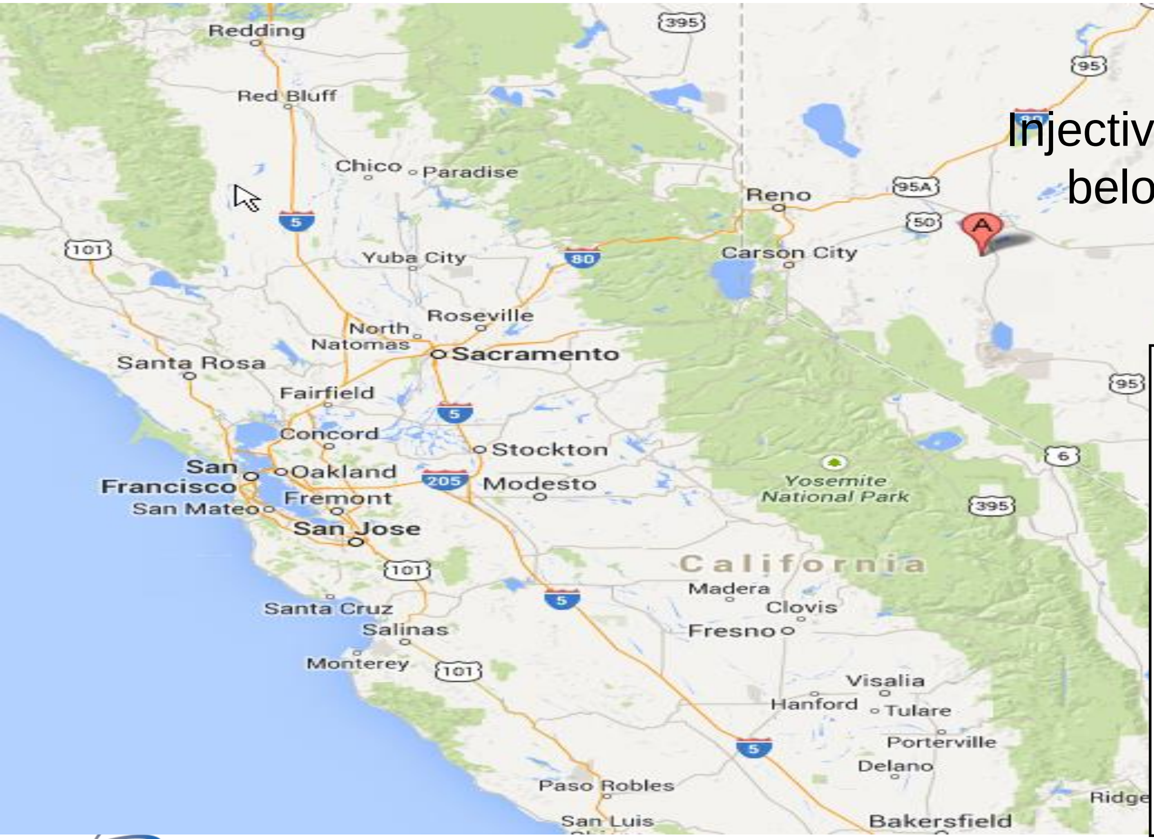


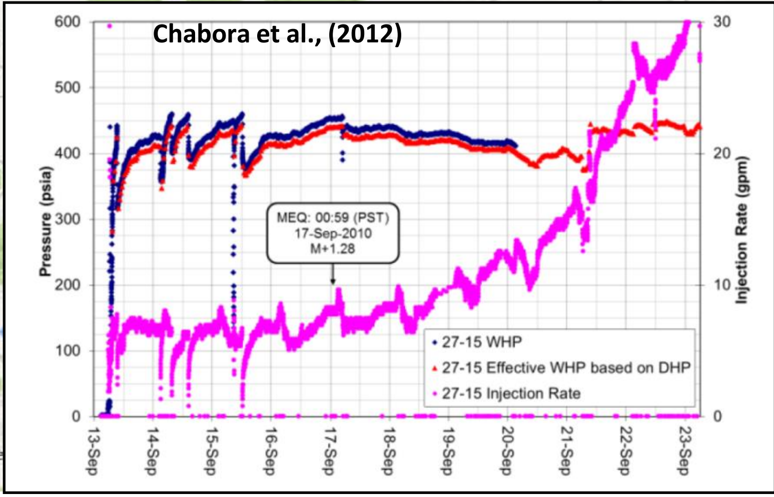




Shear stimulation of Desert Peak well #27-15 in 2010
(Chabora et al. 2012 SGW, Dempsey et al. 2013 ARMA)

Injectivity Improvement at pressures well below Fracture Opening Pressures





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Model Description

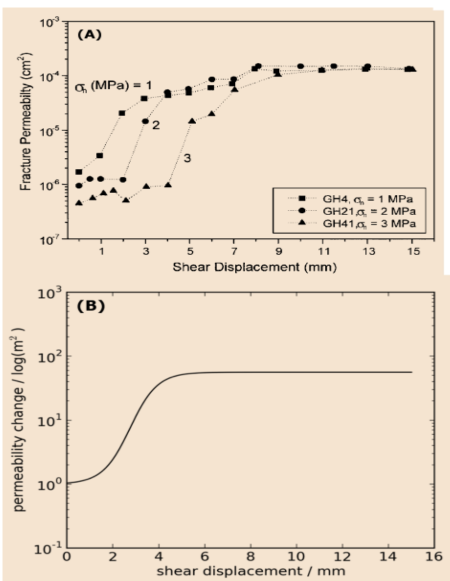
(Dempsey et al. 2013)

T, P modifies σ modifies **PERM.**

Mohr-Coulomb Criteria

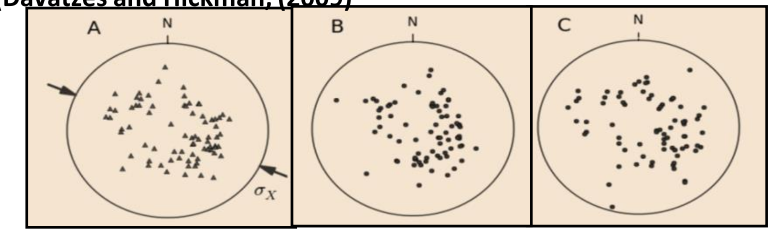
$$\tau - \mu(\sigma_n - p_f) + C > 0?$$

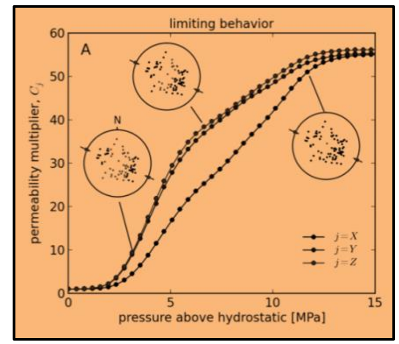
permeability = f (excess shear stress)

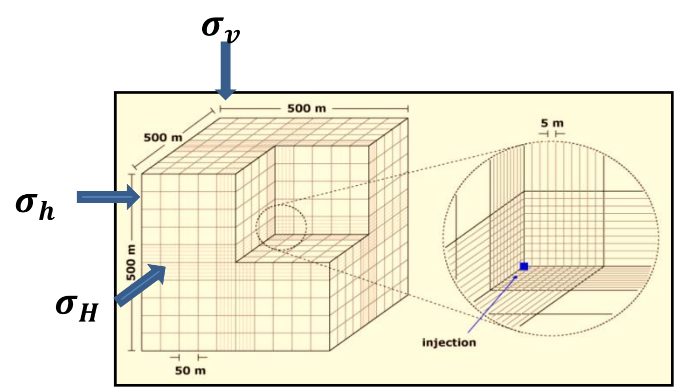


Desert Peak fractures (Davatzes and Hickman, (2009)

Synthetic distributions







Model Results

Low P: 2.2 MPa (350 psi)

•No change in injectivity (useful result)

Medium P: 3.1 MPa (450 psi)

•Injectivity gain at Day 6

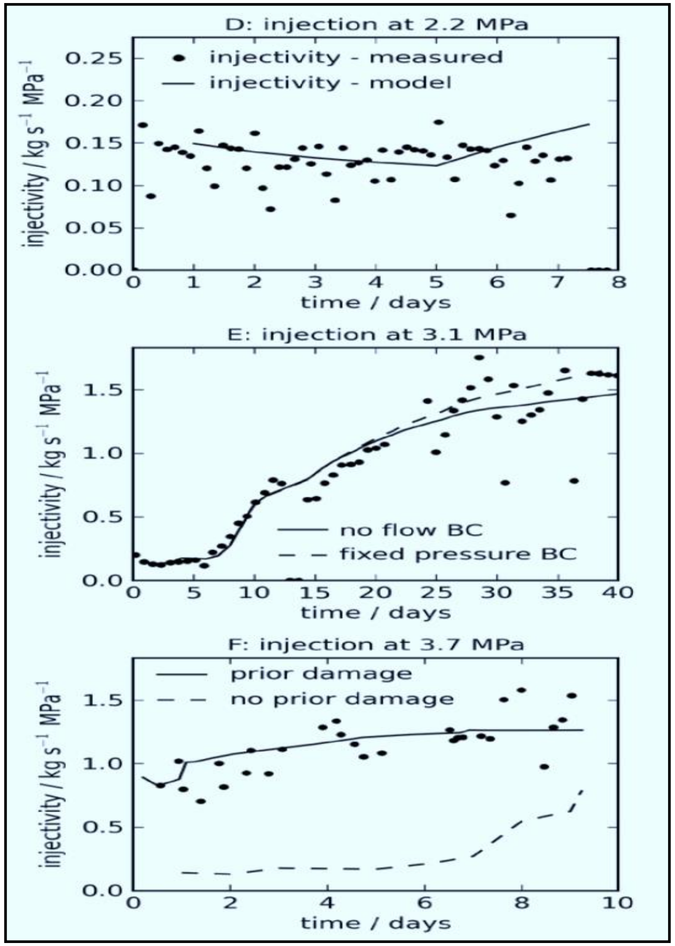
•15-fold increase

High P: 3.7 Mpa (550 psi)

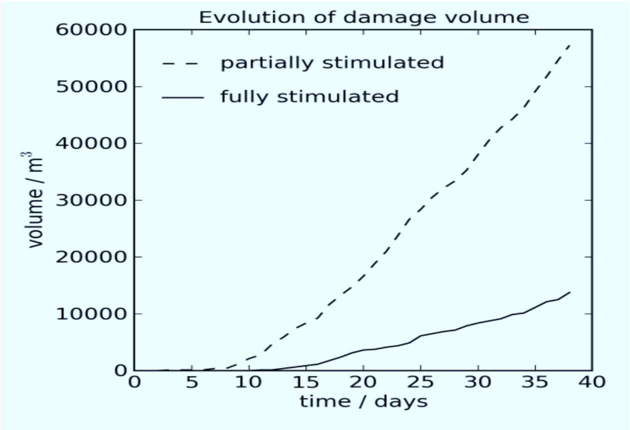
•Injectivity drop

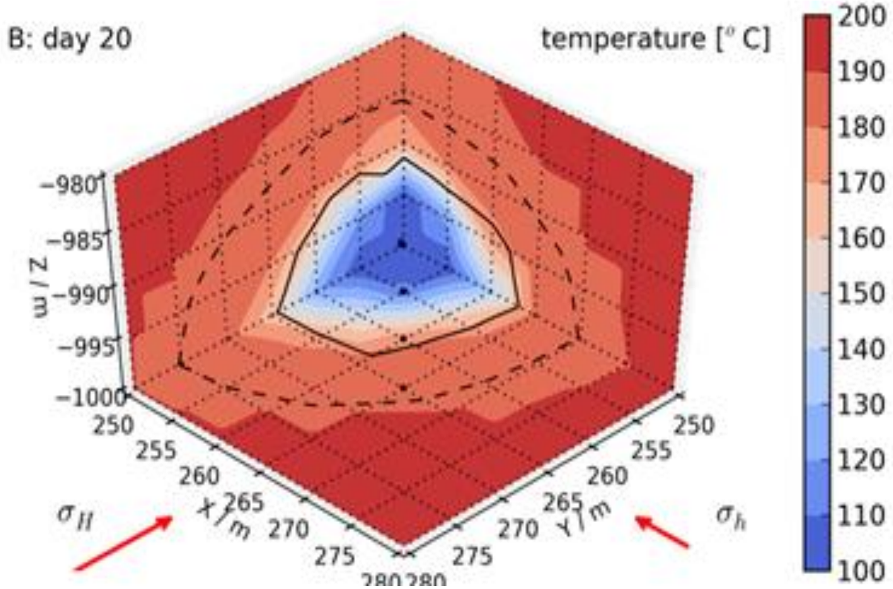
•Some inherited damage (45%)

(shut in for a few weeks)



Model Results (cont)

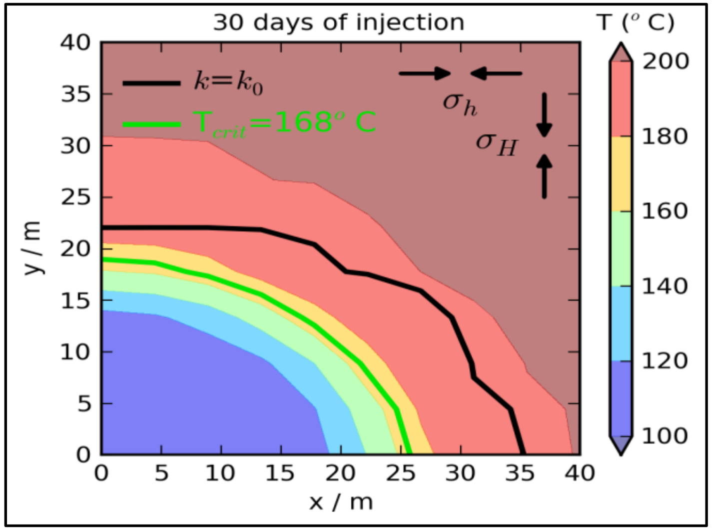


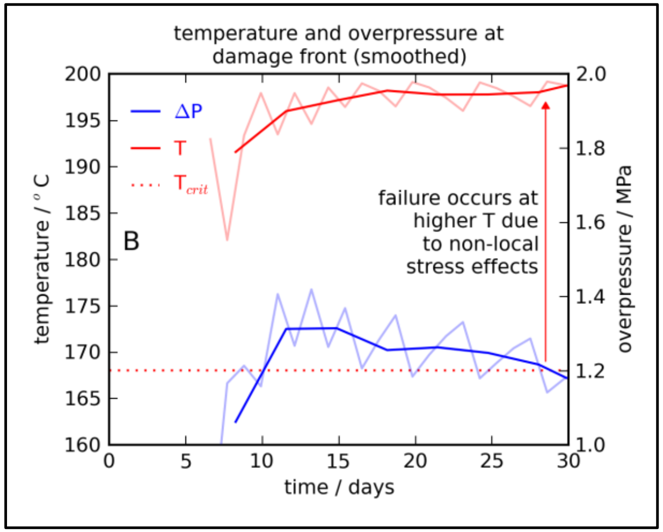


Model Results (cont)

Stress effects are non-local (elliptical equations)

Damage front AHEAD of critical temperature front





Model Results (cont)

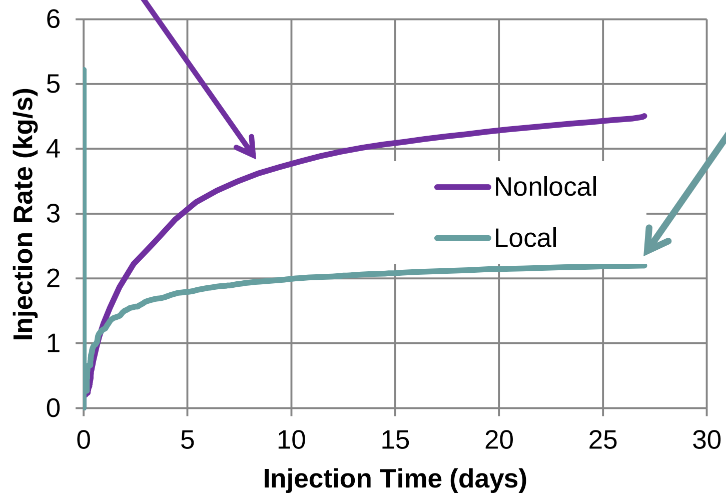
stress effects are Non-local

Mohr-Coulomb Criteria

$$\tau - \mu(\sigma_n - p_f) + C$$

Boundary value
Thermo-Poro-Elastic stress calculation

Local approximation
Far field stresses with local P and T



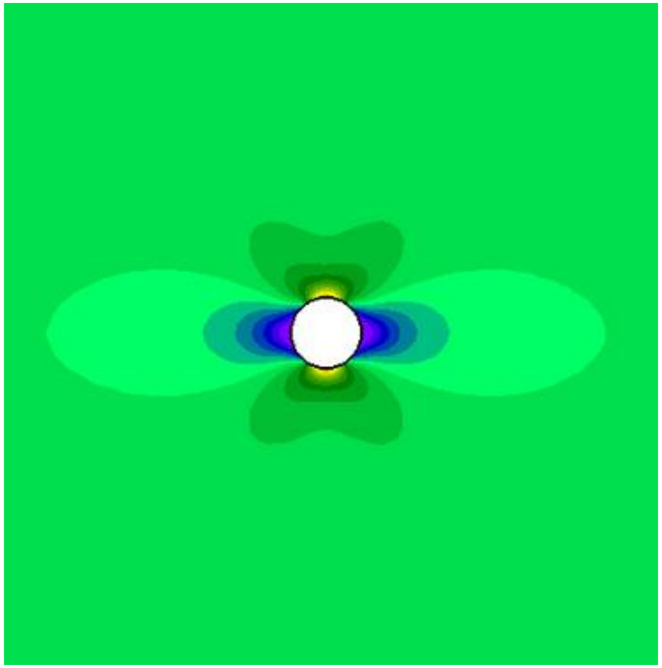
Effects of Plasticity

- **Stress change is limited –Yield**

- **As a bounding scenario, think of the classical Hole-In-Plate**
(i.e. wellbore stability issues caused by stress concentrations)

- **Expect that the failure envelop will be predicted to propagate further by a model including plasticity**

- **Non-local stress effects, coupled with permeability enhancement will propagate further**



Future Work

- **Apply the model to other field sites**
- **Develop models that incorporate the effects of tensile fracture propagation**
- **Model plastic effects in the failed region**

References

Kelkar, S., K. Lewis, S. Karra, G. Zyvoloski, S. Rapaka, H. Viswanathan, P. K. Mishra, S. Chu, D. Coblentz, and R. Pawar. "A simulator for modeling coupled thermo-hydro-mechanical processes in subsurface geological media." *International Journal of Rock Mechanics and Mining Sciences* 70 (2014): 569-580.

Davatzes, N. C., and S. H. Hickman. 2009. Fractures, Stress and Fluid Flow Prior to Stimulation of Well 27-15, Desert Peak, Nevada, EGS Project. In Proceedings of the 34th Workshop on Geothermal Reservoir Engineering, Stanford, 9 – 11 February.

Dempsey D., Kelkar S., Lewis K., Hickman S., Davatzes N., Moos D., and Zymach E. Modeling shear stimulation of the EGS well Desert Peak 27-15 using a coupled Thermal-hydrological-Mechanical simulator. 47th US Rock Mechanics / Geomechanics Symposium held in San Francisco, CA, USA, 23-26 June 2013.

Chabora, E., E. Zemach, P. Spielman, P. Drakos, S. Hickman, S. Lutz, K. Boyle, A. Falconer, A. Robertson-Tait, N. C. Davatzes, P. Rose, E. Majer and S. Jarpe. 2012. Hydraulic Stimulation of Well 27-15, Desert Peak Geothermal Field, Nevada USA. In *Proceedings of the 37th Workshop on Geothermal Reservoir Engineering, Stanford, 30 January – 1 February 2012*.

Zyvoloski, G. A. 2007. FEHM: A control volume finite element code for simulating subsurface multi-phase multi-fluid heat and mass transfer. *Los Alamos National Laboratory Document LAUR-07-3359*. Los Alamos, NM.

Conclusions

•Developed a model to simulate coupled Thermal-Hydro-Mechanical processes in geological media

•Model can match field data from a hydro-stimulation experiment at the Desert Peak Geothermal project in Nevada, USA.

•Stress effects propagate ahead of the thermal and pore pressure disturbances

•Coupled plasticity – permeability modifications expected to be important.

END

Parameters for numerical model

Parameter	Value
Injection depth [1]	1000 m
Injection pressure [1]	2.2, 3.1, 3.7 MPa
Injection temperature[1]	100°C
Material	
Thermal conductivity	2.2 W m^{-1} K^{-1}
Density [7]	2480 kg m^{-3}
Specific heat capacity	1200 J m^{-3} K^{-1}
Porosity [7]	0.1
Coefficient of thermal expansion	3.510^{-5} K^{-1}
Young's modulus [7]	25 GPa
Poisson's ratio [7]	0.2
Reservoir	
Reservoir temperature	190°C
Initial permeability []	1.28,1.54,1.0310^{-15} m^2
	Permeability values increased by 45% of total permeability gain incurred during the preceding 3.1 MPa stimulation.

Young's modulus [7] 25 GPa
Poisson's ratio [7] 0.2
Reservoir
Reservoir temperature 190°C
Permeability values increased by 45% of total permeability gain incurred during the preceding 3.1 MPa

(Dempsey et al. 2013)